

Taiwan Astroparticle Radiowave Observatory for Geo-synchrotron Emissions (TAROGÉ)

C.-C. Chen^a, C.-H. Chen^a, C.-W. Chen^a, P. Chen^a, S.-Y. Hsu^a, J.-J. Huang^a, M.-H. A. Huang^b, T.-C. Liu^a, J.W. Nam^{a*}, Y.-S. Shiao^a, M.-Z. Wang^a, S.-H. Wang^a, T.-L. Zhou^a

^a National Taiwan University, 1 Roosevelt Rd., Taipei, Taiwan

^b National United University, 2 Lianda Rd., Miao-Li, Taiwan

* E-mail: jwnam@phys.ntu.edu.tw

TAROGÉ is an antenna array on the high mountains of Taiwan's east coast for the detection of ultra-high energy cosmic ray (UHECR) in an energy round 10^{19} eV. The antennas will point toward the ocean to detect radiowave signals emitted by the UHECR-induced air-shower as a result of its interaction with the geomagnetic field. Looking down from the coastal mountain, the effective area is enhanced by collecting both direct-emission as well as the ocean-reflected signals. This instrument also provides the capability of detecting Earth-skimming tau-neutrino through its subsequent tau-decay induced shower. A prototype station with 12 log-periodic dipole array antennas for 110-300MHz was successfully built at 1000 m elevation near Heping township, Taiwan in July 2014 to prove the detection concept. It has been operating smoothly for radio survey and optimization of instrumental parameters. We plan to install another station on a higher mountain in summer 2015. In this report, we discuss the design of TAROGÉ, the performance of the prototype station, and the future prospect.

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*Speaker.

1. Introduction

The radio detection method has recently been established as a promising alternative solution for detecting of Ultra-high energy cosmic rays (UHECRs) which is challenging due to the extremely low flux. It would require a detection area several orders of magnitude larger than the current largest cosmic ray detector; Pierre Auger Observatory [1], to identify their astrophysical sources. Radio emission from extensive air showers is a form of geo-synchrotron radiation, which arises from the deflection of electrons and positrons in the shower by the Earth magnetic field. Such radiations at radio-band are coherently added during air-shower development because the radio wavelengths are longer than the shower size, which results in intense pulses that can be detected at a distance of several hundred kilometers. Therefore, one can effectively cover a huge detection area with a small number of radio antennas. Furthermore, the radio detection system can be operated all year round and day-and-night that leads a duty cycle as high as $\sim 100\%$. Several frontier experiments such as LOPES, ANITA, and AREA [2, 3, 4] have demonstrated powerful capability of the radio detection method for UHECR detection. For instance, the ANITA experiment, a NASA balloon-borne antenna array that surveys Antarctica from the altitude of 35 km, reported the observation of 16 events with averaged energy $\langle E \rangle = 1.5 \times 10^{19}$ eV. It turned out that 14 of these 16 events were radio emissions from down-going UHECRs, but reflected off the Antarctic ice surface. ANITA takes an advantage of vast detection area ($\sim 10^6$ km²) within a horizon distance of ~ 600 km from the 35 km of high altitude. Although ANITA has great advantage of covering a large detection area, there are several important drawbacks: 1) the flight duration of the NASA Antarctic balloons is typically limited to ~ 30 days. The duty factor further reduces to 10 days/year since the flight opportunity for such balloon projects is roughly once every three years, 2) ANITA's frequency range is 200-1200 MHz, which is optimized for UHE neutrino detection [5, 6]. In contrast, UHE cosmic ray induced geo-synchrotron radiation is significantly enhanced at lower frequencies down to 10 MHz [7, 8, 9, 10, 11]. Deployment of low frequency antennas to the ANITA payload is difficult due to its weight and space constraints, 3) because the strength of EM signal is proportional to $1/R$, when it propagates through a long distance to the high altitude, only very high energy events can survive and thus lowers event rate, 4) typical altitude of the shower maximum for UHECRs is 10 km, which is much lower than the ANITA's observation point. Only reflected-off signals are detectable except a small fraction of events coming from near the horizon.

2. The TAROGÉ Experiment

Our approach, Taiwan Astroparticle Radiowave Observatory for Geo-synchrotron Emissions (TAROGÉ), is to invoke the proven ANITA detection methodology, but place the antennas at the top of high mountains near the ocean. This approach resolves all problems of ANITA described above. Thanks to the ideal geology of Taiwan's east coast, where there are numerous mountains as high as 2 to 3 km in altitude near ocean. At 2 km altitude the horizon-distance is 160 km, which would provide a 1.3×10^4 km² detection area with a 60° field-of-view. While losing the detection area relative to ANITA, TAROGÉ has a great advantage of year-round operation with a high duty cycle ($\sim 90\%$), which compensates the area loss. Furthermore, lowering the detection frequency range to 100 MHz (and possibly below) and reducing the detection altitude to 2 km would enhance

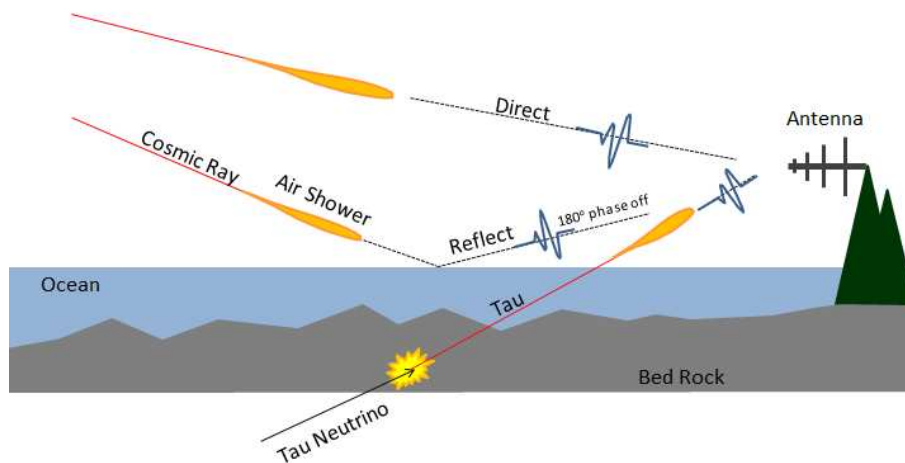


Figure 1: The TAROGÉ-1 Station; Mechanical rendering (left) and figure after the installation completed (right)

the signal strength and would therefore allow TAROGÉ to lower the energy threshold. The sea water is highly reflective for Radio Frequency (RF); the reflection coefficient is near 100% for the horizontally polarized wave, and higher than 60% for the vertically polarized wave except a very small grazing angle. Surface roughness due to ocean wave would be an issue weakening the signal strength. However, this effect is reduced for low frequency range in which the wavelength is longer than the surface roughness for the typical wave condition. TAROGÉ's receiver configuration which points toward the horizon is sensitive to showers with large zenith angles. Therefore one can realize that TAROGÉ is utilized for UHECRS with energies above $10^{18.5} - 10^{19}$ eV. The east side of Taiwan is much less populated than other areas of Taiwan, providing a quieter ambient RF environment. Figure 2 shows power spectra obtained from our initial RF survey at multiple locations in the mountain area of eastern Taiwan. Although many frequency bands appear to be polluted by continuous waveform (CW) noises, there are still fairly quiet bands where the noise floors are comparable to thermal- and Galactic-noises. Using RF filters and a trigger system which is only sensitive to coherent signal, Taiwan could be a feasible place for this experiment. This detection technique not only can be applied in Taiwan, but may also be extended to other places with better and quieter RF environments in future.

3. The TAROGÉ-1 Station

As the first step, in order to demonstrate the detection concept of TAROGÉ and to perform a long-term noise survey, we built a prototype station, TAROGÉ-1, in Yongshih Mt. at 1000 m elevation near Heping township, Taiwan in July 2014. This site had an excellent infrastructure including a good accessibility on a paved road, AC power lines, and a 12m tall truss tower for mounting antennas. Because of a fact which the site has both views of the open ocean and the township in the field of view, it is almost ideal location for a detailed RF noise study with various and strong anthropogenic backgrounds near the coast as well as cosmic ray signals. Figure 3 shows overall structure of the TAROGÉ-1 station. TAROGÉ-1 consists of twelve of 5 dBi log-periodic

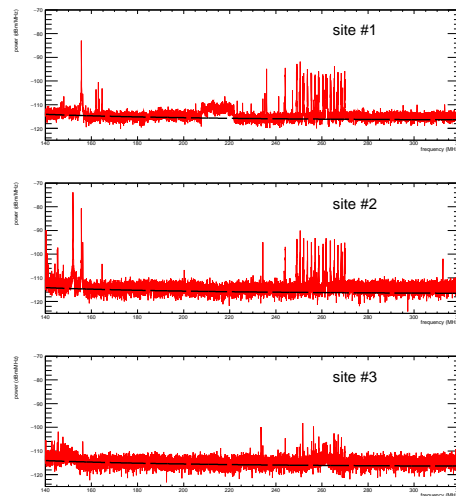


Figure 2: RF noise spectra in the east mountain area: Data taken in a mountain near ocean (top), in a mountain 10km far from ocean (middle), and in a deep valey without ocean view (bottom). Dashed lines indicate estimation of the noise floor contributed by thermal- and Galactic-radiations.

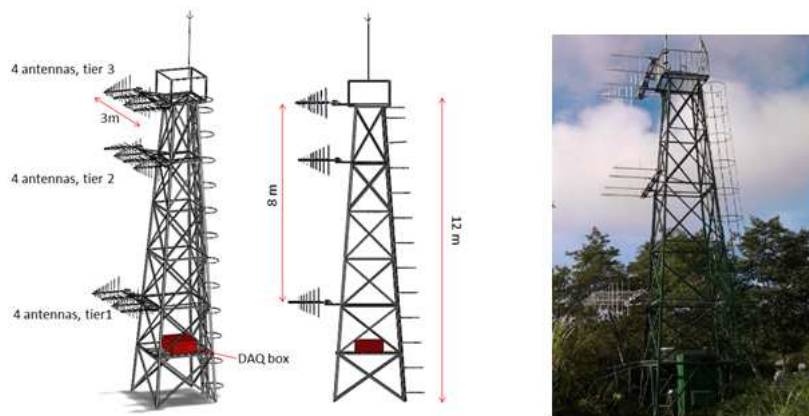


Figure 3: The TAROGÉ-1 Station; Mechanical rendering (left) and figure after the installation completed (right)

dipole array (LPDA) antennas for 110-300 MHz. A dual polarization configuration, the horizontal polarization (H-pol) and the vertical polarization (V-pol), is implemented by orientating E-planes of 6 antennas to the horizontal direction and another to the vertical.

Figure 4 shows the system architecture of TAROGÉ-1. Received signal in the antenna is fed into the RF-front end before the trigger and digitizer system. The RF front-end consists of a front-end filter, a low noise amplifier (+35dB), and a second stage amplifier (+30dB). The RF fronts are located close to the LPDAs to minimize transfer losses. Figure 5 shows a schematic diagram of the TAROGÉ-1 system. The signals are transferred via coaxial cables to the DAQ box where the trigger and digitizer system are placed. In the DAQ box, the RF signals are split into two paths; the trigger and the digitizer.

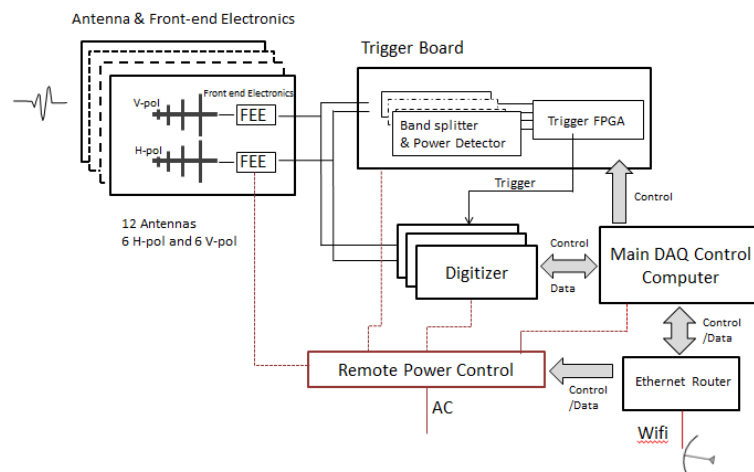


Figure 4: System architecture of TAROGÉ-1

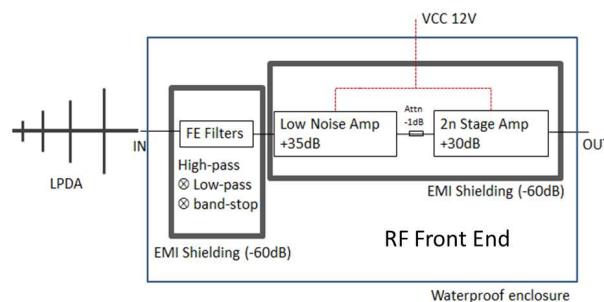


Figure 5: Schematic diagram of RF Front end for TAROGÉ-1

We use the multi-frequency bands coincidence technique, basically similar to ANITA, which provides an effective discriminating-power for impulsive geo-synchrotron signals against thermal noises as well as CW anthropogenic-backgrounds. The thermal noise events are further reduced by requiring multiple antennas coincidence. Figure 6 shows architecture of trigger system. The signal path in the trigger system is fed into four bands; 110-140 MHz, 170-200 MHz, 220-250 MHz, and 270-300 MHz. Uncovered frequency regions between the bands are to avoid communication CW signals along the east coast of Taiwan. Incident increase of RF power is examined by a power detector and a comparator in each band. Individual thresholds of sub-band can be adjusted by multi-channel DACs through remote commands. The thermal noise events are further reduced by requiring multiple antennas coincidence. The dominated emission power of the geo-synchrotron in Taiwan is V-pol because of a low inclination of Earth magnetic field. However, the Askaryan effect in the extensive air-shower still produces a fair amount of power in H-pol [4]. Furthermore, the reflection coefficient of H-pol is much higher than V-pol especially in the low grazing angle which is less than 10 degree. Therefore, we designed the trigger to performe both in H-pol and V-pol, but independently.

The digitizer system uses affordable commercial digital oscilloscopes: GW Instek GDS-

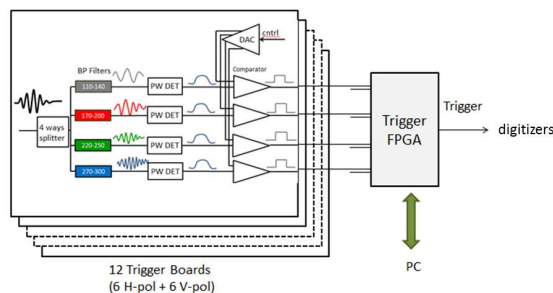


Figure 6: Schematic diagram of trigger system of TAROGÉ-1

2304A with the 300 MHz bandwidth and 8 bit ADCs. We operate the system with 1GHz sampling rate for a record length of $1 \mu s$. The record length is somewhat longer than the optimal configuration, which causes traffic in data transfer to the main computer, but is limited by the company's firmware. The maximum rate of event readout is ~ 7 Hz, which is the bottleneck of the TAROGÉ-1 DAQ. The data size is 50KBytes/s (or 4.3GBytes/day) after compression. Real-time data transfer and system control is available through the internet. We use a long range Wi-Fi repeater with 24dBi dish antennas linking between the TAROGÉ station and the Edu-net at Heping elementary school in the township. All active elements of the system are placed in Faraday boxes to ensure EMI shielding with shielding power better than -60 dB. Waterproof enclosures are also used to protect electronics and to prevent change of impedance of RF connectors for severe mountain weather conditions.

A precise geometry survey was carried out to measure coordinates of antennas, which is crucial to ensure a good pointing capability. A laser theodolite with an arc-sec angular resolution was used to provide a precision of 1 mm. After completed the installation of station, system validation and calibration were followed using a calibration pulser system which consists of an impulsive pulse generator and a LPDA antenna. The transmitter power was varied using an adjustable attenuator, and polarization angle was varied by changing tip-tilt angle of an antenna mount on a tripod. The pulser signals were sent from multiple locations near the coastal line where its distance to the TAROGÉ-1 station is 3-5km. Because the oscilloscope readout reached the saturation rate due to numerous numbers of impulsive noises from the township, triggering on the pulser events was challenging unless a high threshold signal-to-noise ratio ($SNR > 10$) was required.

Figure 7 displays recorded waveforms of one of the pulser events. The timing calibration was performed using the pulser events. We used the cross-correlation technique [16] to measure arrival time difference between antennas. As shown in Figure 8, we achieved an excellent timing resolution ~ 80 ps for $SNR = 10$ signals for antenna pairs connected to the same oscilloscope. The antenna pairs in different oscilloscopes has ~ 400 ps time resolution which is dominated by the trigger jitter of the oscilloscope. This jitter, in principle, can be removed if the oscilloscopes are synchronized. Several synchronization methods have been proposed, for instance to use the phase information of external sinusoidal waves which added into RF signals before the digitizer. The frequency of this synchronization signal can be chosen out of the TAROGÉ bands.

We use the interferometry imaging method [17] to determine the arrival direction of the incoming RF signal. Figure 9 shows an interferometry image obtained from the calibration pulser event.

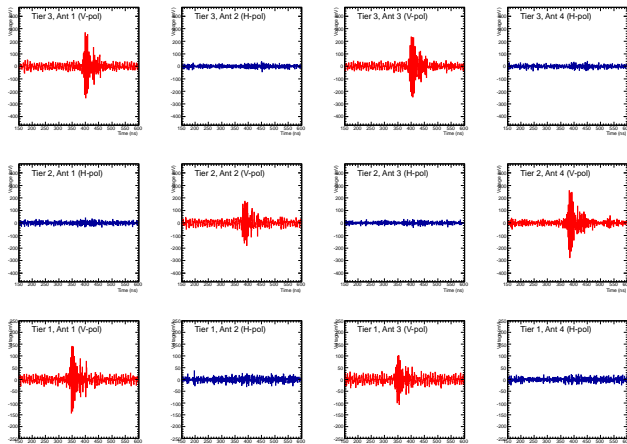


Figure 7: Pulser event waveforms (V-pol event)

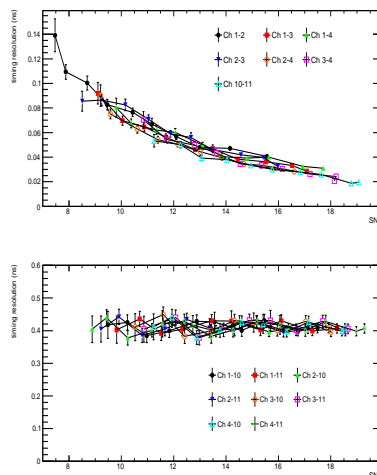


Figure 8: Time resolution versus SNR: channels in the same board (top) and channels in different boards

Figure 10 shows an excellent angular resolutions, which is better than 0.15 degree in elevation angle and 0.45 degree for horizontal angle, are achieved.

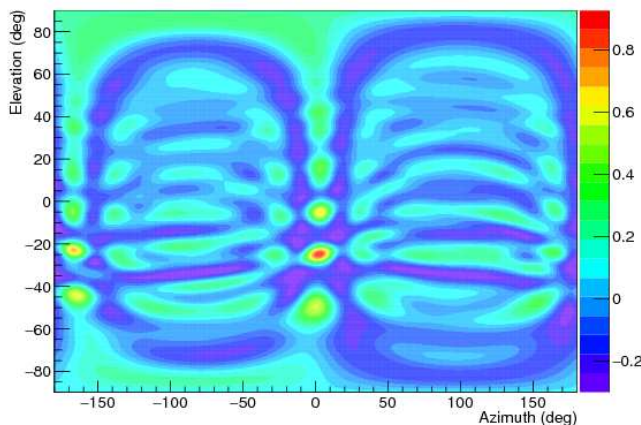


Figure 9: Interferometry image of the calibration pulser event

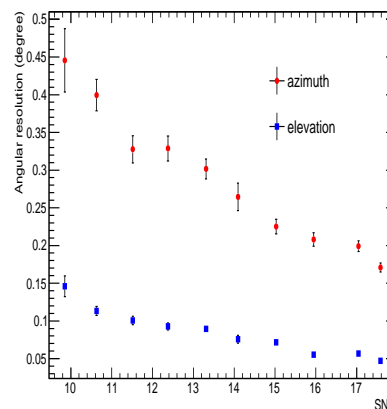


Figure 10: Angular resolution versus SNR

TAROGÉ-1 has been operating smoothly upto now since the beginning of August 2014. There are some non-operating periods during severe weather conditions as like typhoons, power outages due to failure of power line, and maintenances and minor upgrades of the system. Overall operation time is more than 7 months during past 11 months. The system operated remarkably stable with a duty cycle almost 100% during winter and spring.

4. Discussions

Several important lessons from TAROGÉ-1 are to be addressed both for system upgrades and

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extensions in future. As we described earlier, operating the trigger system in a low level of threshold are restricted by the severe impulsive noises near the TAROGÉ-1 site. The noise sources are mostly identified to be in the township. As an upgrade plan, we are going to install veto antennas pointing toward the township. High gain horn antenna would be a good option for the veto in order to minimize the loss of the detection area. The LPDA antenna design can also be modified for the higher gain. Increasing the boomlength of LPDA by 50% can provide a gain of 7dBi, which helps reduce the antenna response to the township direction, and also increase the sensitivity to the signals. An inclined orientation of the boresight of LPDA toward the sky by 10-20 degrees can be considered. For the TAROGÉ-2 station, we found a new site where impulsive noises from the township are drastically suppressed. However, the direction to Hualian which is the biggest city in the east coast and has a local airport, is only 60 degrees off from the middle of the field of view of the new site. Since CW noises from Hualian now become an issue, a new trigger system must be developed not sensitive to the CW noises. For instance, increasing the number of sub-frequency bands would be a feasible solution. The readout rate of the digitizer is to be improved. TAROGÉ-2 is going to use a new oscilloscope which has a factor of ten higher readout rate and a higher bandwidth (350MHz) than TAROGÉ-1. With these improvements, we are going to build the TAROGÉ-2 station in October 2015 aiming to begin observation of UHECR events.

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